Fine Coal Flotation in a Centrifugal Field With an Air Sparged Hydrocyclone

J.D. Miller and M.C. Van Camp

Abstract—*Preliminary results are reported regarding the design and development of a pilot scale air sparged hydrocyclone for cleaning fine coal 590 µm (−28 mesh) containing 24% ash and 1.6% sulfur. The principle of separation is the flotation of hydrophobic coal particles in the centrifugal field generated by the fluid flow in the air sparged hydrocyclone as discussed in another publication. This 152-mm (6-in.) hydrocyclone has a nominal capacity of 0.9 t/h (1 tph) and experimental results suggest that separations vastly superior to a water-only cyclone are possible. In addition the separation efficiency is as good, if not better, than that achieved with conventional flotation cells. For example, typical results indicate that 75% clean coal can be recovered at 15% ash leaving a tailing product of almost 50% ash. These experimental results coupled with the high capacity of the air sparged hydrocyclone (imagine a retention time for flotation of only two seconds compared to two minutes for conventional flotation) may represent a significant breakthrough, not only in coal preparation technology, but in the flotation of fine particles in general.*

Introduction

Many factors—political, environmental, and technological—will determine the extent to which the US realizes the potential of its vast coal resources. Not the least of these factors is technological development including mining, processing, and transportation. With regard to processing technology, about 50% of the 726 Mt/a (800 million tpy) tons of coal mined annually in the US is processed in preparation plants. The purpose of the physical separations accomplished in these preparation plants is to remove ash (present as clays and other oxide minerals) and sulfur (present mostly as pyrite). Coal flotation circuits for such separations are becoming more important in the processing of-590 µm (-28 mesh) coal (Miller, Podgursky, and Aikman, 1967; Aplan, 1979; and Burger, 1980). For example in the US in 1960, 31 flotation plants processed 24 kt/d (26,500 tpd); whereas in 1980, there were 80 flotation plants which processed 71 kt/d (78,300 tpd). This corresponds to an annual growth in flotation plant capacity of 10% per year during the past two decades.

Coal flotation is based on the natural or induced hydrophobicity of coal particles that are separated from hydrophilic ash and sulfur constituents by attachment to air bubbles. The coal particle/air bubble aggregates are collected in a froth phase that is created by the addition of a suitable frother such as MIBC. Without exception, such separations are made in a conventional flotation cell, which, in essence, is a stirred tank reactor with a shrouded rotor to shear the air as it passes through a hollow shaft. The dispersed air bubbles ~ 1-mm-diam (0.04 in.) are stablized by addition of the frother. Collision of the air bubbles with, and/or precipitation of the air bubbles on, the coal particles results in the formation of coal particle/air bubble aggregates that rise in the gravitational field and are collected in the froth phase developed at the top of the flotation cell. Restraints on successful separation by this conventional flotation technique are particle size and retention time. Generally it is found that effective flotation is only achieved for particle sizes between 10 µm and 1-mm (1250-18 mesh). Further, with respect to retention time, it is found that a nominal retention time of at least two minutes is required for successful separations. These facts limit the effectiveness of conventional coal flotation. Coal fines may be lost in the reject stream and disposal is frequently a problem. The retention time required for conventional flotation results in large floor space demands and limits the capacity of the plant.

Consideration of the hydrodynamic flow and the centrifugal force field developed in such cyclonic devices as the hydrocyclone and Dyna Whirlpool together with the anticipated effect on the flotation behavior of hydrophobic particles has led to the development of a new type of flotation device, an air sparged hydrocyclone (Miller, 1981; and Miller and Van Camp, 1981). Unlike a conventional flotation cell, in this new equipment thin film, swirl flotation is accomplished in a centrifugal field by air sparging through a porous wall. Because of the phenomena occurring in this innovative air sparged hydrocyclone, separation of fine hydrophobic particles can be readily accomplished and retention times can be reduced to a matter of seconds. In this regard, some theoretical discussion of the flotation process is offered followed by a description of the air sparged hydrocyclone. Finally, some preliminary results indictive of the separation effectiveness are presented.

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Flotation Principles in a Centrifugal Field

It might be anticipated, under certain circumstances, that flotation in a centrifugal field would extend the fine particle flotation limit and increase the flotation rate. Preliminary results indicate that these effects are observed in the air sparged hydrocyclone. A simplified theoretical analysis of flotation in a centrifugal field explains these anticipated and observed effects. More detailed analysis has been reserved for another publication (Miller, Kinneberg, and Van Camp, 1982).

Particle Size

The ineffective separation of fine particles has been recognized as a serious limitation in froth flotation for some time and a general discussion on this subject has been presented recently (Fuerstenau, 1980; and Jowett, 1980). Figure 1 is indicative of this phenomenon and presents both experimental observations and theoretical predictions for the rate of flotation as a function of particle size. It can be noted that the fine particle flotation limit may be anywhere from 10 μm to 1 mm (1250-18 mesh) depending on the particular mineral system.

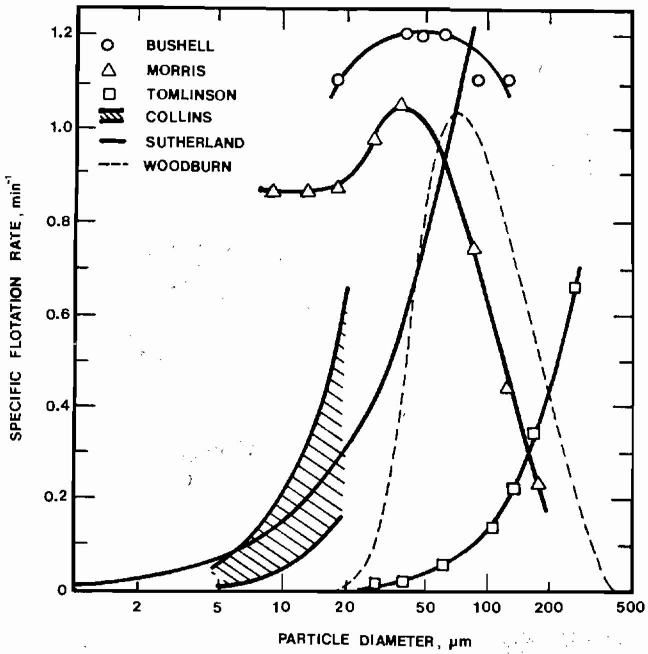

Fig. 1—The effect of particle size on both experimental and predicted flotation rates for both sulfide and nonsulfide flotation systems (Fuerstenau, 1980).

If the probability of collision and attachment of particle with bubble is considered from the standpoint of inertial impaction, a particle size can be defined below which impaction should not occur. Under these circumstances the particle has insufficient inertia to deviate from the fluid streamlines. The Stokes number, which is a measure of the ratio of inertial forces to viscous forces, is a convenient criterion to determine the extent to which particles will deviate from streamlines and undergo inertial impaction with another body, a bubble. Using a critical Stokes number of 0.1 and other physical properties of the system, a particle size can be calculated below which inertial impaction does not occur. This critical size depends on the magnitude of the force field and as can be seen from Fig. 2 for normal gravitational fields of 1G the critical size for impaction is on the order of the size limit for fine particle flotation. Further, note that as the force field increases, the critical size for inertial impaction drops rapidly reaching a size of 1 μm (12000 mesh) at about 100 Gs.

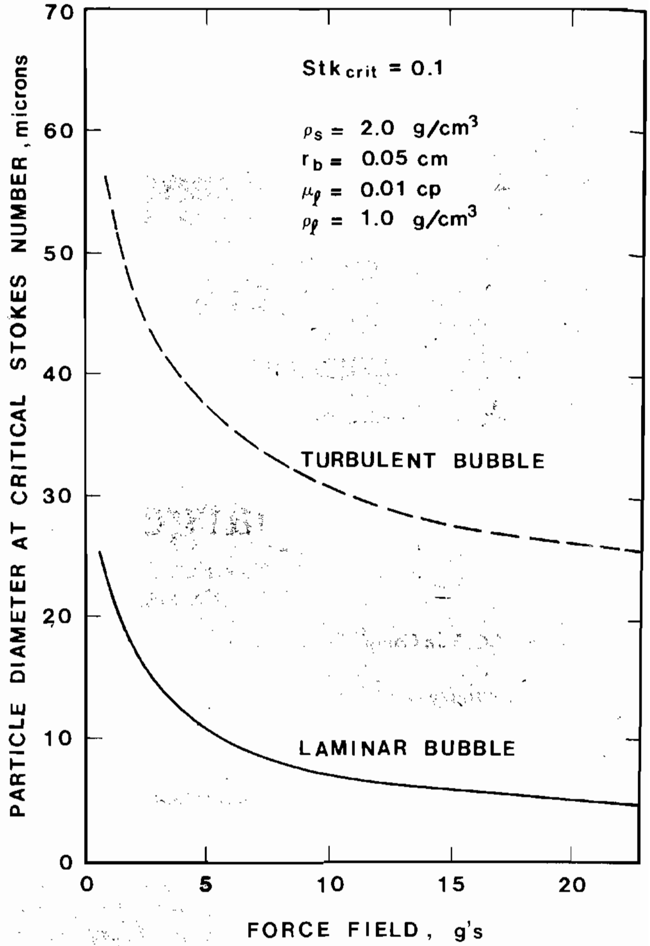

Fig. 2—Minimum particle diameter for inertial impaction as a function of the force field magnitude assuming a critical Stokes number of 0.1 (Miller, Kinneberg, and Van Camp, 1982).

Flotation Rate

The Sutherland equation is a useful expression to study the effect of physical variables on the flotation rate (Sutherland, 1948).

$$\text{Recovery} = 1 - \exp(-kt) \tag{1}$$

$$k = 3\pi\beta d_b d_p u N \operatorname{sech}^2\left(\frac{3u\lambda}{4d_b}\right) \tag{2}$$

In Sutherland's equation, the first order rate constant k is proportional to particle size and bubble size, d_p and d_b, the relative particle-bubble velocity u, the concentration of air bubbles N and a complex function combining the induction time λ, the relative speed, and bubble size. The proportionality factor β is a collision/attachment efficiency factor. For higher force fields the relative particle-bubble velocity should increase and the induction time should decrease. Further analysis of Sutherland's flotation rate equation has been given by Jowett (1980). From consideration of the hydrodynamic flow regime as well as the variation of induction time with particle size and velocity it can be shown (Van Camp, 1981) that the flotation rate constant is directly proportional to the magnitude of the force field:

$$k = (\text{Force Field})^a \tag{3}$$

where,

$$0.5 < a < 1$$

The practical significance of this analysis is that in a device such as an air sparged hydrocyclone, force fields of at least 50 Gs can be achieved which suggests that the fine particle flotation limit could be extended to perhaps 1μm (12000 mesh) and that the rate of flotation could be 50 times the rate of flotation in a gravitational field. Indeed, such a tremendous rate increase would be required for an air sparged hydrocyclone inasmuch as the retention time in such cyclonic devices is only on the order of seconds.

Air Sparged Hydrocyclone

Centrifugal fields can be generated either by mechanically rotating devices such as centrifuges or by conversion of pressure head into rotational motion as found in hydrocyclones. The latter approach leads to a simple, less expensive and more robust design which is to be preferred in the mineral industry.

Design Considerations

In cyclonic devices, the vortex created by the rotational motion of the liquid can be free or forced depending on the design of the hydrocyclone. See Fig. 3. Free vortices tend to occur in systems where the majority of the flow leaves the apparatus axially as in a classification hydrocyclone. Under these conditions the tangential velocity is maximal at an intermediate distance from the center. Physically, the free vortex is created due to the angular momentum transport from the wall to the center. In a forced vortex, the whole fluid rotates at the same angular velocity resulting in a wheel-like motion and the tangential velocity decays to zero. This type of hydrodynamic regime decreases the axial flow of the liquid leaving the cyclone.

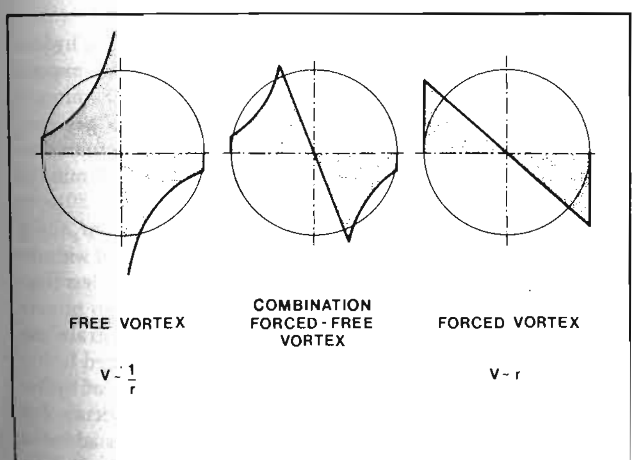

Fig. 3—Vortex types created by the rotational motion of the liquid flow in cyclone devices.

A number of different designs of the air sparged hydrocyclone have been tested and results reported at several professional society meetings (Miller 1981; and Miller and Van Camp, 1981). In addition, a detailed account of this research is given in a recently completed MS thesis by M.C. Van Camp (1981). Basically, the various designs that have been tested are shown in Fig. 4. As can be noted, these designs include not only inclined orientations but also vertical orientations with an option for axial feed injection (Miller and Van Camp, 1981). Such an option provides the possibility of processing both coarse and fine particles in different hydrodynamic regimes of the same device. The preferred design is a vertical oriented, cylindrical cyclone with tangential feed at the top. Whatever orientation and feed entry system are selected, the basic features of the air sparged hydrocyclone are a porous wall through which air is passed and a tangential flow of slurry orthogonal to the air flow. As might be anticipated, a critical factor in the performance of the air sparged hydrocyclone is the water split. Whatever geometry or orientation is selected, water flow to the froth concentrate must be minimized and this was a major factor in the selection of the preferred design.

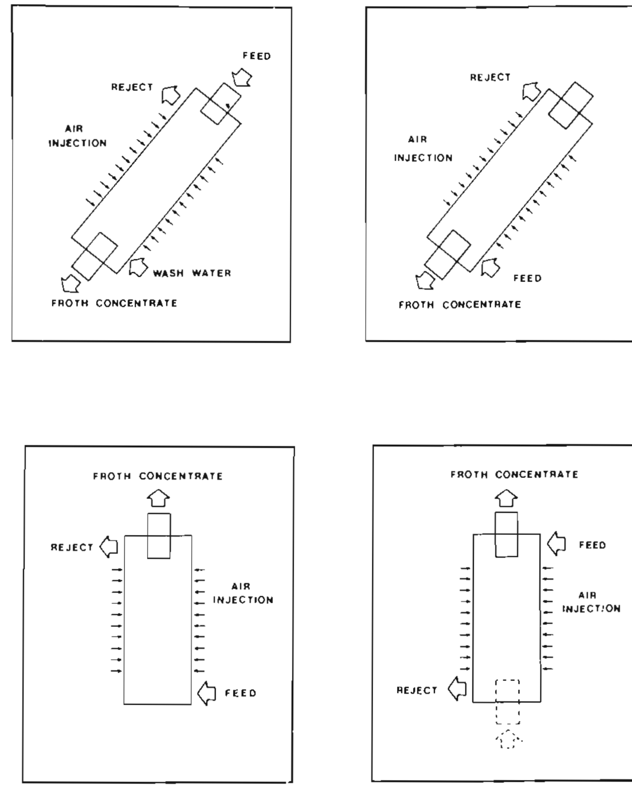

Fig. 4—Air sparged hydrocyclone designs tested for flotation separation.

Principles of Separation

Basically the preferred design, a schematic of which is shown in Fig. 5, provides for forced vortex flow and since the tangential velocity component does not go through a maximum near the axis of the cyclone, a quiescent froth phase develops in the center of the separator. Further, water transport with the froth phase to the overflow is minimized. These features are of significant importance to the success achieved in flotation separations with the air sparged hydrocyclone.

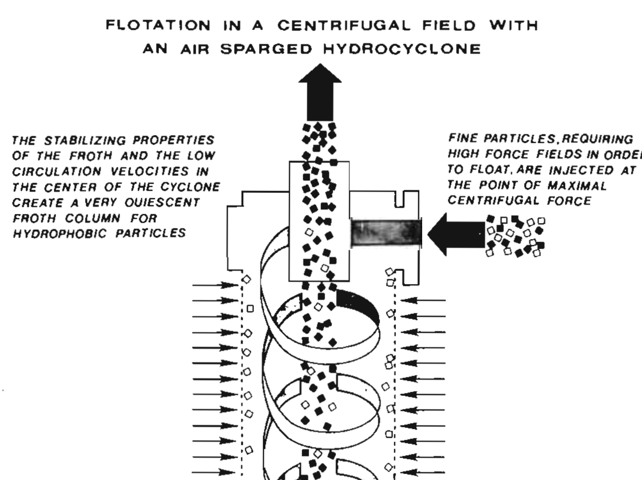

Fig. 5—Schematic drawing of the preferred air sparged hydrocyclone design.

Further, the slurry that is fed tangentially at the top of the air sparged hydrocyclone passes through the separator as a thin film in swirl flow and moves countercurrent to the froth phase in an axial direction. The slurry phase occupies less than 10% of the cyclone volume. Hydrophilic ash and sulfur particles are thrown to the porous cylinder wall and are discharged tangentially in the reject. Hydrophobic coal particles encounter the air bubbles sparged radially through the porous cylinder wall. The high shear force field at the porous cylinder wall generates small air bubbles and provides for intense particle/bubble interaction. Hydrophobic particle/air bubble attachment occurs and the hydrophobic coal particles are transported into the froth phase which exits axially at the tòp of the air sparged hydrocyclone.

The flow regime found in the air sparged hydrocylone is depicted in Fig. 6. It appears from photographic evidence (Van Camp, 1981) that a fully developed forced vortex exists which accounts for the tangential velocity profile. The froth phase occupies more than 90% of the separator volume and the surface of zero axial velocity appears to be close to the froth-slurry "phase boundary." In view of the spatial relationship and the difference in velocity vectors of the froth phase and slurry phase, it can be appreciated that the retention times for the respective phases will differ significantly. For example, for the six inch air sparged hydrocyclone the slurry retention time is estimated to be less than one second.

To summarize, the rapid flotation rate achieved in the air sparged hydrocyclone involves generation of small air bubbles and intense particle/bubble interaction at the surface of the porous cylinder due to the high shear force field, followed by transport of the hydrophobic particle/air bubble aggregates through a thin film of slurry in swirl flow into the froth phase. In essence flotation in the air sparged hydrocyclone results in constrained particle/bubble interaction rather than the random particle/bubble collisions which exist in conventional flotation cells. Most importantly, these constrained particle/bubble interactions occur rapidly in the centrifugal field developed in the air sparged hydrocyclone.

Experimental Results

Preliminary experiments with a 150 mm (6 in.) air sparged hydrocyclone have been completed using a 590 μm (-28 mesh) coal slurry taken from the feed stream to a water-only hydrocyclone circuit in a preparation plant operated by the Cerro Marmon Coal Group at Boswell, PA. The dewatered coal was delivered wet in 208 L (55 gal) drums and sealed in two-fold polyethylene plastic bags to prevent oxidation. The-590 μm (-28 mesh) coal was found to contain a significant amount of fines with from 50-70% finer than 38 μm (400 mesh). The ash content varied from 22-25% with most of the ash in the -38 μm (-400 mesh) size interval. For the experimental results reported, Dowfroth 1012 was used as frother.

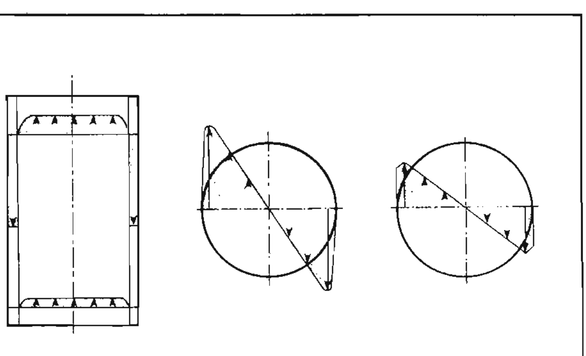

Fig. 6—Axial, tangential and radial velocity profiles for the flow regime in the preferred air sparged hydrocyclone design.

Air Sparged Hydrocyclone Circuit

The air sparged hydrocyclone used in this study had an inside diameter of 150 mm (6 in.). Standard headers with involute entrance and exit ports were used at the top and bottom. The steel jacketed porous cylinder was a high density polyethylene with an average pore size of 10 μm. Lengths of 406 mm (16 in.) and 737 mm (29 in.) were tested. Other sparging cylinders have been constructed from porous stainless steel material and tested. Air for the separator was supplied from a compressor and the porous cylindrical sections were made with quick connect fittings. Air flow was measured with standard rotameters.

The air sparged hydrocyclone circuit consists of a 600 L (159 gal) sump with a 3.7 kW (5 hp) centrifugal pump for feeding the coal slurry. Products from the flotation separation are sampled with two automatic samplers and the remaining material in the clean coal and reject are disharged for disposal. Slurry flow is controlled using a Doppler flowmeter and the signal is transferred to a proportional integrating controller which in turn positions the electromagnetic valve at the desired flow rate. The accuracy of this flow control is very satisfactory and the system can handle any slurry flow rate between 0.08-4.2 L/s (1.3-66 gpm).

Comparison with Batch Flotation

The quality of separation achieved with the air sparged hydrocyclone is comparable to that achieved in batch flotation experiments. Results from conventional batch flotation for two minutes with an Agitair bench cell and 0.25 kg/ton (0.5 lb per ton) Dowfroth 1012 are presented in Table 1 and are compared to results obtained with the air sparged hydrocyclone (737 mm (29 in.) porous cylinder, air flow rate 6.6 L/s, (106 gpm), 20 ppm Dowfroth 1012, 3% solids, feedrate 4 L/s (63 gpm) or about 0.45 t/h (0.5 tph) dry solids). The yield of 75% obtained with the air sparged hydrocyclone for a slurry retention time of less than 0.5 second is better than the yield obtained in the two minute batch flotation experiment and the results demonstrate the rapid flotation rate that can be realized in the air sparged hydrocyclone. The separation is indeed due to the flotation of hydrophobic particles and hardly any separation by size occurs. For example, when an organic colloid coal depressant was added to the sump the yield dropped to 11%. Size classification effects are minimized due to the minimal water flow to the froth phase (comparable to conventional flotation) and the fact that fine hydrophilic particles would have to be transported through the froth phase for exit to the overflow.

Table 1—Comparison of the Performance of an Air Sparged Hydrocyclone with the Performance of a Conventional Batch Flotation Cell

	Air Sparged Hydrocyclone	Batch Flotation
Clean Coal, % Ash	16.0	15.5
Reject, % Ash	49.0	46.8
Yield, %	75.0	67.0

Air Flow Rate

The effectiveness of the separation shows a significant dependence on the air flow rate as shown in Table 2. It can be noted from the results that the recovery of clean coal increases substantially to 75% at the higher air flow rate with little effect on the ash content of the products and little effect on the fraction of the feed water reporting with the clean coal overflow product.

Table 2—The Effect of Air Flow Rate on the Separation Efficiency (29 in. porous cylinder, 20 ppm Dowfroth 1012, 3% solids, feed rate 240 L/min or about 0.5 tph dry solids)

	Air Flow Rate	
	200 Lpm	400 Lpm
Clean Coal, % Ash	16.7	16
Reject, % Ash	42.6	49
Yield, %	52.0	75
Water Split	0.2	0.2

Cyclone Length

Undoubtedly an important design variable will be the length of the air sparged hydrocyclone. An increase in length will increase the retention time of the slurry which is anticipated to move in plug flow. On the other hand, at some length the tangential velocity component and centrifugal force will be reduced to such an extent that no advantage from the centrifugal force field will be realized. Analysis of swirl flow hydrodynamics in a vertical cylinder is in progress and indications are that the length to diameter ratio can be as high as 10 to 1.

Preliminary results presented in Table 3 indicate that an increased retention time due to an increase in length significantly improves the separation efficiency for the same air flux of 100 Lpm/ft^2 which corresponds to an air velocity of 0.01 m/s (3.5 fpm).

Table 3—The Effect of Porous Cylinder Length on the Separation Efficiency at an air flow rate of ~100 Lpm/ft^2. (20 ppm Dowfroth 1012, 3% solids, feed rate 240 L/min or about 0.5 tph dry solids).

	Cell Length	
	16"	29"
Clean Coal, % Ash	22.5	16.0
Reject, % Ash	37.5	49.0
Yield, %	59.5	75.0

Particle Size

The behavior of individual size intervals during flotation in the centrifugal field was examined. It was found that the coarser particles required a longer retention time, but generally good separation was realized for all size intervals. Ash analyses and yields for the complete distribution have been presented in previous tables. The behavior of each size interval and the nature of the countercurrent flow for froth and slurry are shown in Fig. 7 for the 737 mm (29 in.) porous cylinder. By sampling the froth phase along the axis of the cyclone an estimate of the ash profile in the axial direction has been obtained for each size interval. It can be noted that the most effective separation occurs in the (-38 μm) (-400 mesh) interval in which most of the material is found. The coarser size intervals contribute only a small amount to the total mass and as can be noted, these coarser intervals do not contain as much ash. Nevertheless the ash content of the coarser sizes has been reduced significantly. The greatest ash reduction, however, occurs for the -38 μm (-400 mesh) size interval in which the ash content is reduced from 36% in the feed to 23% in the clean coal product. The overall ash content of the clean coal product is 16.6%.

Summary

Preliminary experiments with an innovative air sparged hydrocyclone indicate that coal flotation separations can be achieved with a separation efficiency equivalent to that achieved with a conventional flotation cell. Typical results for a high ash (24%) -590 μm (-28 mesh) coal feed containing 50-70% -38 μm (-400 mesh) material indicate that 75% of the coal can be recovered at about 15% ash leaving a tailing product of almost 50% ash.

Performance of the air sparged hydrocyclone for ash removal in fine coal cleaning is compared with other fine coal cleaning techniques in Table 4.

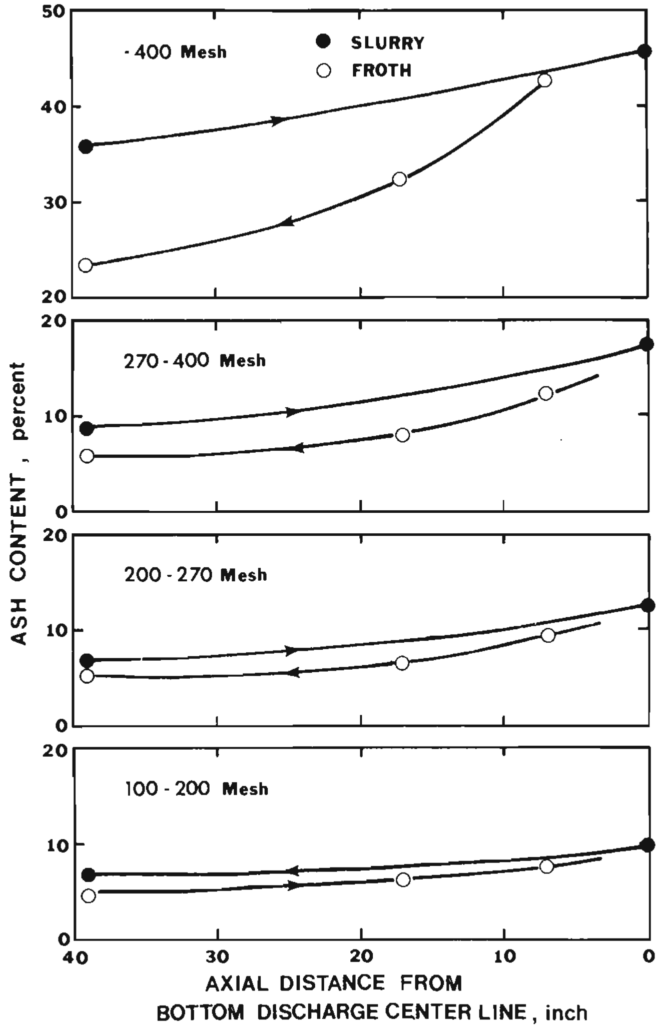

Fig. 7—Axial ash distribution in froth and slurry for various particle size intervals.

Table 4—Effectiveness of Different Techniques for Ash Removal in Fine Coal Circuits with Respect to Particle Size

	Ash Removal, Percent				
Particle Size (Mesh)	Water Only Cyclone[1]	Single Stage Flotation [1]	Air Sparged Illinois No. 6	Hydrocyclone Beaver Creek	15-75 Lower Kittaning
28 × 100	60-65	50-60	77-86	84.2-	70.4
100 × 200	40-45	40-45	59-68	70.2	39.6
200 × 325	15-18	40-45	44-62	77.0	42.5
—325	0-5	50-55	57-67	81.0	54.0

These experimental results for the flotation of fine coal when considered with the high capacity of the air sparged hydrocyclone (retention time of less than a second compared to minutes for conventional flotation) may represent a significant breakthrough, not only in coal preparation technology, but in the flotation of fine particles in general. The tremendous potential of this device is indicated by the preliminary comparison made in Table 5 and certainly the results obtained justify continuation of this research and development program.

Table 5—Preliminary Comparison of Conventional Flotation Cells With the Air Sparged Hydrocyclone

	Conventional Flotation Cells	Air Sparged Hydrocyclone
Capacity, tpd/ft^3	1-2	50
Energy Consumption, kwh/ton	0.75-1.5	0.3
Area, ft^2/tpd	0.33-0.1	0.01
Air, ft^3/min/ft^2	3-5	2
Cost, \$(1971)/tpd M & S index 300	7-17	5*

* Estimated to be 2.5 times the cost of a classification hydrocyclone

Particle-bubble interaction and transport involve more complex phenomena than simply the inertial impaction analysis presented. Important phenomena which contribute to the rapid flotation of fine particles are identified in Table 6. Basically in the hydrocyclone's centrifugal field the slurry, in swirl flow, encounters the radial flow of air through the porous cylinder wall.

Table 6—Phenomena Contributing to the High Flotation Rate of Fine Particles in an Air Sparged Hydrocyclone

1. Centrifugal force field—increase particle and bubble inertia
2. Generation of numerous small air bubbles by high shear force at the porous wall surface
3. Directed rather than random interaction of particles with the freshly formed air bubbles at the porous wall surface
4. Transport of particle/bubble aggregates a short distance through the layer of slurry in swirl flow into the froth phase.

The high shear forces at this surface generate numerous small bubbles and provide for directed and constrained particle/bubble interaction. Hydrophobic particle/air bubble aggregates are transported through the thin film of slurry into the froth phase which moves countercurrent to the pulp and exits axially in the overflow. The hydrophilic particles remain in swirl flow and exit tangentially at the bottom of the air sparged hydrocyclone. □

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